

# **Low-cost, single-frequency sources for spectroscopy using conventional Fabry-Perot diode lasers**

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## **Abstract**

Commercial (uncoated) Fabry-Perot laser diodes are converted to single-frequency spectroscopy sources by passively locking the laser frequency to the band edge of a fiber Bragg grating, which phase-locks the laser oscillations through self-injection seeding.

## Low-cost, single-frequency sources for spectroscopy using conventional Fabry-Perot diode lasers

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The wide bandwidth characteristic of the gain media of diode lasers makes them good sources for spectroscopy. In order to achieve the required spectral purity, however, either a DFB or DBR device must be fabricated, which incurs significant development costs for every target wavelength. Conversely, conventional Fabry-Perot diode lasers can be fabricated relatively cheaply, and their design does not preclude operation at any wavelength within the gain bandwidth. Unfortunately, their laser oscillations do not stabilize at one single-frequency, hopping chaotically between modes instead. This instability has been circumvented previously by two methods that employ a grating in an extended cavity configuration<sup>1,2</sup>. Here we demonstrate stable, CW, single-frequency operation from a non-AR coated Fabry-Perot laser diodes using only FBG optical feedback.

The basis for the demonstrated frequency stabilization lies in the nature of the reflected light from a fiber Bragg grating. In the standard coupled-mode formalism<sup>3</sup>, the reflection spectrum of a FBG is derived from two counter-propagating modes, which are constrained by the structure of the two coupled differential equations to take the following form (in the notation of Erdogan<sup>4</sup>):

$$\begin{aligned} R(z) &\equiv A(z) \exp(i(\delta z - \phi/2)) \\ S(z) &\equiv B(z) \exp(-i(\delta z - \phi/2)) \end{aligned} \quad (1)$$

where  $\phi/2$  is the phase of the incident beam at  $z = 0$ , the middle of the FBG. When light is reflected from a mirror, the phase of the reflected light is always  $\pi$  out-of-phase with respect to the incident light. However, the relative phase of light reflected from a FBG, is given by  $\rho \exp(-i(\delta L - \phi))$ , where  $L$  is the length of the grating, and  $\rho$  is the amplitude ratio at  $z = 0$ :

$$\rho = \frac{-\kappa \sinh(\sqrt{\kappa^2 - \hat{\sigma}^2} L)}{\hat{\sigma} \sinh(\sqrt{\kappa^2 - \hat{\sigma}^2} L) + i\sqrt{\kappa^2 - \hat{\sigma}^2} \cosh(\sqrt{\kappa^2 - \hat{\sigma}^2} L)} \quad (2)$$

Moving the source of the incident light induces a shift in the incident phase,  $\phi \rightarrow \phi + \Delta\phi$ , under which the phase of the two modes transforms as:

$$\begin{aligned} R(z) &\rightarrow \exp(-i\Delta\phi/2) R(z) \\ S(z) &\rightarrow \exp(i\Delta\phi/2) S(z) \end{aligned} \quad \Rightarrow \rho \rightarrow \exp(-i\Delta\phi) \rho \quad (3)$$

In other words, the spatial variation of the phase of the reflected beam is conjugate to that of the incident beam (modulo the phase of  $\rho$ , which depends only on wavelength)--this property can be reconciled conceptually by regarding the phenomenon as a one-dimensional four-wave mixing experiment whose hologram has been written permanently during an earlier exposure.

At the short-wavelength band edge ( $\hat{\sigma} = +\kappa$ ) the phase of  $\rho$  is zero ( $\kappa$  is real for single-mode fiber), so that light reflected at this wavelength will interfere constructively at its source, regardless of the source's location. If a diode laser is temperature tuned so that the wavelength of the an axial mode coincides precisely with the short-wavelength band edge of a FBG, the reflected light will seed the laser with feedback that constructively reinforces only that axial mode, phase-locking the laser oscillations.

We coupled a nominally 935 nm Fabry-Perot laser diode (Sensors Unlimited) into an angle-cleaved, ultra narrow-band (18 pm), 16% reflectivity FBG (Kromafibre, Inc.) with a reflection peak at 935.625 nm using the configuration depicted in Fig. 1. The laser temperature was controlled by an analog TEC with 1 mK resolution (Wavelength Electronics HTC 3000). The emission at the laser facet was imaged 1:64 onto a beam profiler (BeamScan), and the spectrum

characterized using an OSA (HP 7000A), a wavemeter (Burleigh WA-1500), and a scanning Fabry-Perot étalon (Burleigh). The optical-heterodyne measurement of the single-frequency linewidth used a Si-PIN detector (ThorLabs DET 210) and an RF spectrum analyzer (HP 8590A).

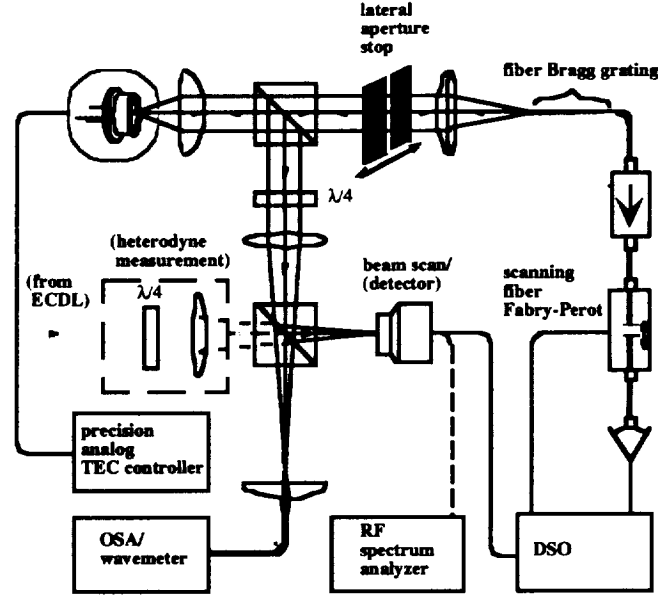


FIG. 1. Experimental setup including linewidth measurement (dashed lines)

For best coupling into single-mode fiber, the astigmatic laser beam was collimated on the fast axis, placing the virtual beam waist of the slow axis  $5 \mu\text{m}$  behind the facet. To accommodate the resulting mode mismatch with the anastigmatic feedback signal, we used a variable aperture stop on the slow (lateral) axis of the collimated beam. This displaced the lateral focus of the feedback signal<sup>5</sup> to coincide with that of the laser for a slit width of  $1.45 \text{ mm}$ .

We tuned the laser wavelength, subject to feedback from the FBG, by varying its temperature. The spectral purity of the output, as measured by side-mode suppression ratio, is seen in Fig. 2 to track the reflectance curve of the FBG, offset about  $-3 \text{ pm}$  to the band edge of the grating:

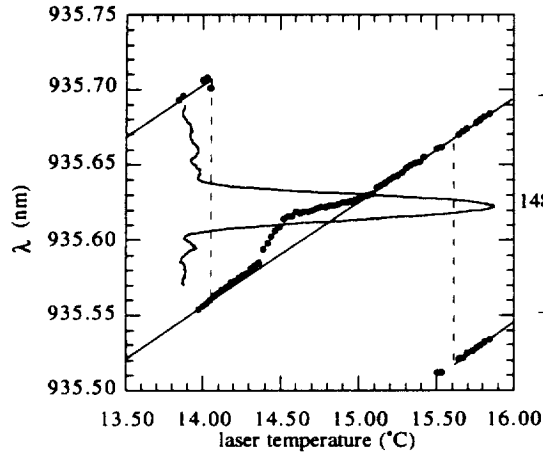


FIG 2A. Laser output vs. T overlaid on Reflectance spectrum of FBG

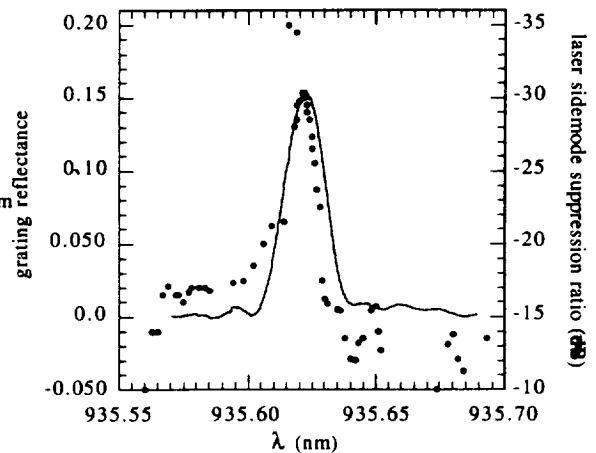


FIG. 2B. Laser spectral purity overlaid on reflectance spectrum of FBG

Detailed examination of the outlying points at the top of Fig. 2 using a scanning Fabry-Perot reveals the spectra in figure 3: Off the band edge, the spectrum is broad; Slightly off the band

edge, the spectrum is seen to comprise several phase-stabilized submodes that span about 7 GHz—the approximate bandwidth of the FBG; The spectrum displays true single-frequency operation precisely on the band edge, also plotted in Fig. 3.

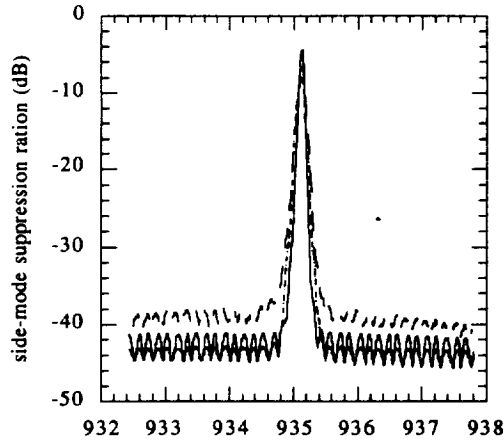


FIG 3A. OSA spectra of off-band-edge

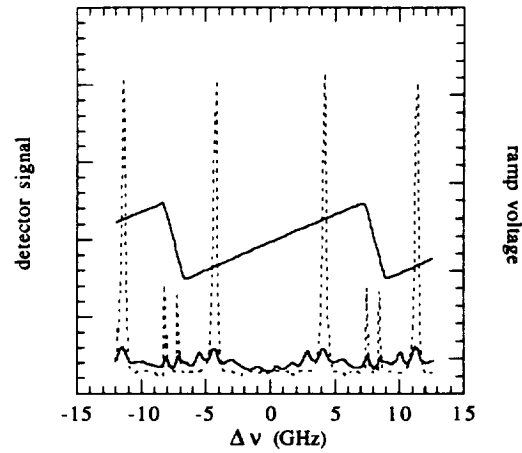


FIG. 3B. Scanning Fabry-Perot spectrum of single-frequency (dotted line) and phase-stabilized spectrum

We characterized the linewidth of the laser by mixing the laser output (935.625 nm) with the output from an ECDL<sup>6</sup> tuned to 935.624 nm and measuring the RF spectrum of the power beat note at the detector. The instantaneous (20 ms) linewidth was 225 MHz (not shown) and the time averaged (2 s) linewidth was 470 MHz (Fig. 4).

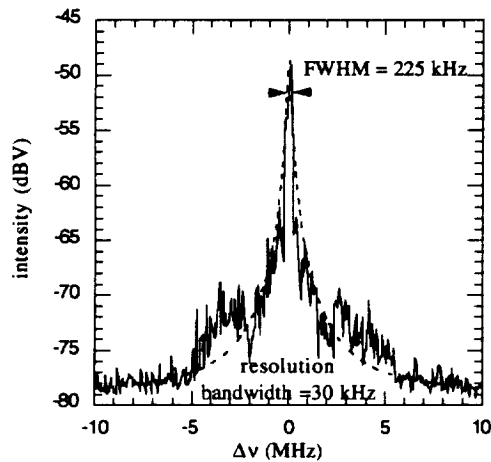


FIG 4A. Instantaneous (20 ms) RF spectrum

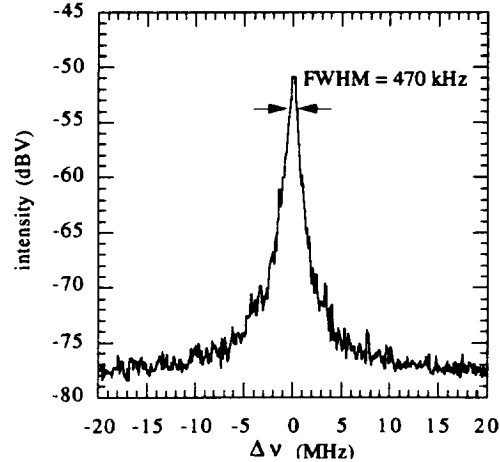


FIG 4B. Time averaged (2 s) RF spectrum

The P-I characteristic curve (not shown) shows that single-frequency operation lowers the lasing threshold by 15.3% and increases the slope efficiency by 5.3%. This experiment was also repeated with an SDL 5431 high-power laser at 825 nm and an SDL 7311 buried heterostructure laser at 666 nm. In the first case, the slope efficiency was doubled, and the second case did not require a lateral aperture for stop single-frequency operation (-50 dB side-mode suppression). We infer from this result that rigidly confining the gain region within the confines of the waveguide sufficiently reduces spatial variation of the gain profile to nearly eliminate astigmatism and the associated mode-mismatch phase ambiguity.

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